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Macroeconomic impacts of bioenergy production on surplus agricultural land—A case study of Argentina

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ABSTRACT

This paper assesses the macroeconomic impacts in terms of GDP, trade balance and employment of large-scale bioenergy production on surplus agricultural land. An input–output model is developed with which the direct, indirect and induced macroeconomic impacts of bioenergy production and agricultural intensification, which is needed to make agricultural land become available for bioenergy production, are assessed following a scenario approach. The methodology is applied to a case study of Argentina. The results of this study reveal that large-scale pellet production in 2015 would directly increase GDP by 4%, imports by 10% and employment by 6% over the reference situation in 2001. When accounting for indirect and induced impacts, GDP increases by 18%, imports by 20% and employment by 26% compared to 2001. Agricultural intensification reduces but does not negate these positive impacts of bioenergy production. Accounting for agricultural intensification, the increase in GDP as a result of bioenergy production on surplus agricultural land would amount to 16%, 20% in imports and 16% in employment compared to 2001.

Contents

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1. Introduction

Since sustainable bioenergy production should not endanger food production, cause deforestation or increase the environmental pressure on land, an option for large-scale bioenergy production could be land that is freed from agriculture by increasing the efficiency of agricultural production [1]. This agricultural intensification, defined as the increase in the productivity of land through changes in labour, capital and/or inputs, can be made possible by applying more efficient agricultural production systems and optimising the use of land for agricultural production [2]. According to a study by Smeets et al. [2], in theory, up to 70% of the current global agricultural land area could be freed in 2050 by applying very efficient agricultural production systems, taking population growth, GDP growth and dietary changes into account. But this change in agricultural production systems may have negative macroeconomic impacts as it is generally associated with increased mechanisation and decreased labour needs and, in turn, could reverse the positive macroeconomic impacts associated with bioenergy production [3–8]. Since increasing land availability for bioenergy production through agricultural intensification is an important instrument in ensuring the sustainability of bioenergy [1], investigating the overall macroeconomic impacts of large-scale bioenergy production in developing countries requires examining the combined impacts of bioenergy production and agricultural intensification. However, previous studies have not accounted for agricultural intensification and the resulting macroeconomic impacts [3–8]. Thus, the main objective of this study is to evaluate the overall macroeconomic impacts of bioenergy production on presumed surplus land assuming gradual agricultural intensification and introduction of biomass crops and a bioenergy sector.

The macroeconomic impacts of bioenergy production and agricultural intensification are quantified by employing input–output (*I*/*O*) analysis because of its successful application in previous studies on the macroeconomic impacts of bioenergy [3,4,6,9,10], its ability to assess not only direct but also indirect and induced impacts,[1,2] and its statistically consistent and systematic approach to understanding the economic impact of a new economic activity. While *I*/*O* analysis does have drawbacks such as a time lag between the year that data is collected and the year the *I*/*O* tables are available, constant returns of scale and the inability to account for price effects, it allows for an assessment of economy-wide impacts disaggregated for individual economic sectors, which explains why it is a valued and frequently used analytical tool [12]. This study uses *I*/*O* analysis to determine the direct, indirect and induced macroeconomic impacts on the following variables: *GDP* (measuring the effect on the size of a country's economy), *balance of trade* (measuring the changes in the country's dependence on other countries and its possibilities for generating income from exporting to other countries) and *employment* (measuring the immediate impact on the population).

The methodology developed in this study is applied to the case of large-scale lignocelluloses crop production and conversion to pellets and in a second chain also to Fischer–Tropsch (FT) fuel in Argentina. This choice of case study is based on the large projected bioenergy potentials in Latin America [2,13], favourable climate and soil conditions for growing biomass, low land and labour costs that reduce the overall production costs, and high-quality existing infrastructure and human resources that could facilitate the introduction of large-scale bioenergy production and logistics in the near future in Argentina.

The remainder of the text is structured as follows. Section 2 describes the methodology applied to investigate the macroeconomic impacts of bioenergy production on surplus agricultural land, including a description of input–output analysis and the modifications applied by this study. Section 3 defines the input data used in the analysis and is followed by the presentation of results (Section 4). Section 5 follows with a discussion of the suitability of Argentina as a case study, critical aspects of the *I*/*O* model and the underlying assumptions of agricultural intensification. Section 6 presents the study's final conclusions.

2. Approach

2.1. Bioenergy

This study accounts for all steps in bioenergy production that occur within the borders of the producing country, Argentina. Processes included are land preparation, planting, operation and maintenance of the plantation, harvest, transport and storage, pre-treatment and final conversion. Assuming that the final product is largely exported, final (international) transport, storage, retail and final consumption are not included.

While many bioenergy chains are possible, two likely chains for Argentina are selected and their macroeconomic impacts compared: *Chain 1* covers eucalyptus wood production and pre-treatment to pellets as well as storage and transportation at the various stages of the production chain. *Eucalyptus grandis* is chosen as the biomass source because of its promising growth yield in central and north-eastern Argentina and its recognition as a possible energy crop in Argentina [14,15]. A coppice production system with a rotation time of 4 years and four rotations are assumed. After harvesting, the logs are manually forwarded to the side of the road where the wood dries naturally to a moisture content of 26% (from originally 54%) within 3 months [14]. From the roadside, the eucalyptus logs are transported by truck to a central gathering point (at an average distance of 10 km), where the pre-treatment plant is located. For pre-treatment of the eucalyptus, a large-scale pellet production unit with an annual

[1] The direct impacts are those impacts caused by bioenergy production directly (e.g. employment on a bioenergy plantation); indirect impacts are those of the secondary economic activities needed to make bioenergy production possible (e.g. employment in producing machinery required on the plantation) and induced impacts are those caused by the re-spending of the income and profits earned from the direct and indirect activities (e.g. employment caused by additional spending from plantation workers).

[2] Because wood production in developing countries is highly labour intensive, biomass production can generate additional income that is, in turn, assumed to be spent on household goods and services, thereby contributing to the growth of the economy. Since this factor can be quite large, it is important to also include the induced impacts in the analysis of macro-economic impacts of bioenergy production [11].

production of nearly 80 000 t is chosen. Pellets are transported by truck to the export terminal at an average distance of 300 km.[3]

Chain 2 covers the same processes as *Chain 1* but also incorporates a final conversion of the pellets to Fischer–Tropsch (FT) fuel at a plant near the export terminal. The main components of the FT fuel production process are gasification (pyrolysis unit and entrained flow gasifier), gas cleaning and conditioning, FT synthesis and co-generation of electricity. The FT plant is chosen to have a thermal input of 830 MW_{LHV}, processing 4400 t of pellets per day [17].

2.2. Agricultural intensification

Agricultural intensification is modelled according to the Quickscan model of Smeets et al. [2], which was originally set up to calculate the regional and global theoretical biomass potential in 2050 and to analyse the relevant underlying factors that affect the potential. It determines surplus land by comparing the current use of agricultural land with the agricultural land demand from projections of population growth and per capita food consumption and assuming a certain production efficiency and level of agricultural technology [2].

The Quickscan model is applied here to assess the total potential surplus land available in Argentina in 2015. The intermediate level of advancement in agricultural technology of the Quickscan model is chosen because it requires the least changes in the production system and is also the most feasible of those systems presented by Smeets et al. [2] within the given time frame. The intermediate level of agricultural technology refers to some use of fertilizers, pesticides, improved seeds and mechanical tools (for agricultural crop production) and to some use of breeding, feed supplements and dedicated animal housing (for animal production) [2]. Table 1 presents the characteristics of the current and the projected agricultural production system in Argentina.

The Quickscan model estimates the technical potential of surplus land and, therefore, does not account for limitations caused by economic profitability of bioenergy production or institutional and social constraints [2]. But the extent of surplus land influences the magnitude of the macroeconomic impacts. The results of this study are, therefore, checked for their sensitivity to a changing amount of surplus agricultural land (Section 4.4) and the uncertainty in applying the Quickscan model is discussed in Section 5.3. In addition, there are certainly competitors for any surplus land other than bioenergy production. Actual availability for bioenergy will depend on, for example, the price of food, fodder and energy crops and the structure of the land market. However, accounting for these aspects exceeds the scope of this study. Furthermore, not allowing bioenergy production to comprise all of the surplus land would result in this study in an unfair comparison if all the impacts of the intensification are attributed to the bioenergy production. Applying all surplus agricultural land to bioenergy production (and here to only one single bioenergy crop) does not mean to suggest that the total surplus land should be planted with one crop or solely bioenergy crops. This extrapolation is simply used to be able to determine the magnitude of impacts of large-scale bioenergy production on surplus land.

2.3. I/O model

The macroeconomic impacts of bioenergy production on surplus agricultural land are assessed with the help of input–output analysis. *I/O* analysis studies the relationships within and between economic sectors of a country and can be used to determine the impacts of an economic activity on the whole economy [18–22]. In matrix format, the *I/O* model can be represented by

$$X = AX + Y \tag{1}$$

where X is total output, Y is the final demand and A is the technology matrix, defined by the technical coefficients of production (a_{ij}) that represent the value of the input from sector i used in making a dollar's worth of output in sector j.

In order to simulate the new activity in the Argentinean economy, bioenergy production is added as a new sector to the technology matrix,[4] which then takes the following form:

$$A' = \begin{bmatrix} \tilde{A} & \tilde{C} \\ A_{(n+1)} & \tilde{c}_{n+1} \end{bmatrix} \tag{2}$$

where vector $\tilde{C}$ represents the technological coefficients describing the input of other, original industries that are necessary to produce

Table 1
Characteristics of Argentinean agricultural system in reference situation and for intermediate level of agricultural technology in 2015 (source: [2]).

	Reference	2015
Population (million people)	38.4	43.5
Food consumption (kcal cap^{-1} day^{-1})	3 166	3 374[a]
Crop yields (kg ha^{-1})		
Cereals	3 692	8 861
Roots	25 898	23 308[b]
Sugar crops	6 347	6 892
Pulses	1 250	2 250
Oil crops	5 186	4 667[b]

	Pastoral	Mixed	Pastoral	Mixed
Animal production–feed composition (%)				
Beef	56	44	0	100
Milk	31	69	0	100
Mutton and goat	55	45	0	100
Pork	0	100	0	100
Poultry and eggs	0	100	0	100

	Pastoral	Mixed	Mixed[c]
Animal feed conversion efficiency[d,e] (kg dry weight feed kg^{-1} animal product)			
Beef	60.2	67.7	32.5
Milk	2.1	2.8	1.8
Mutton and goat	159.6	151.7	85.0
Pork	–	6.6	6.6
Poultry and eggs	–	4.1	3.5

[a] The assumed increase of food consumption is based on the average calculated for South America. Since Argentina now has an average calorie intake per day higher than the South American average (3166 calories per capita per day in Argentina versus 2850 for South America [30]), the assumed food intake increase may be larger than in reality, causing an overestimation of food intake and therefore an overestimation of required food production.

[b] Yields of roots and oil crops are lower in 2015 than in 1998. This is due to several reasons, among others, that, due to optimisation of land use, lower quality land may be used for these crops. For a description of the allocation procedure see [2].

[c] Differences in the current and future mixed production system can be attributed to the composition of the feed.

[d] As feed conversion efficiencies are only available for regional data, Argentina's feed conversion efficiency is assumed to be the same as that of South America.

[e] It can be observed that the feed conversion efficiency of the pastoral feeding system is higher than the mixed feeding system (less feed is needed to produce one kilogram of product). This shows how efficient the pastoral production system can be with respect to converting feed to product. However, the feed production is much more efficient in the mixed feeding system because of much higher crop yields than grass yields on pastures.

[3] Truck transport is currently the most common form of transportation in Argentina despite its high costs compared to transport by rail or water [16].

[4] For reasons of simplicity, the following description of the methodology is based on introducing one new industry to the economy. However, it is possible to introduce several new sectors in the same way.

one unit of output of the new industry; $\tilde{c}_{n+1}$ is the input from the new industry itself to produce one unit of its own product; $A_{(n+1)}$ is a row vector that represents the necessary input of the new industry to produce a unit of output in the original industries; and matrix $\tilde{A}$ is the new technology matrix of the original industries. It is different from the original matrix A because of the assumption that the intermediate input share in the total output is unchanged after the new industry is added. As a result, the new sector's technical coefficients are subtracted from other input coefficients of the sector in which the new sector's products are used.

With the addition of this new sector to the technology matrix, the I/O model becomes:

$$(I - A') \times X' = \begin{bmatrix} (I - \tilde{A}) & -\tilde{C} \\ -A_{n+1,j} & (1 - \tilde{c}_{n+1}) \end{bmatrix} \times \begin{bmatrix} X \\ x_{n+1} \end{bmatrix} = \begin{bmatrix} Y \\ y_{n+1} \end{bmatrix} = Y' \quad (3)$$

or in terms of changes:

$$(I - A') \times \Delta X' = \begin{bmatrix} (I - \tilde{A}) & -\tilde{C} \\ -A_{n+1,j} & (1 - \tilde{c}_{n+1}) \end{bmatrix} \times \begin{bmatrix} \Delta X \\ \Delta x_{n+1} \end{bmatrix} = \begin{bmatrix} \Delta Y \\ \Delta y_{n+1} \end{bmatrix} = \Delta Y' \quad (4)$$

where x_{n+1} and y_{n+1} are the new sector's output and final demand, respectively.

The general I/O model is demand driven; that is, the change in final demand is considered exogenous. However, in this study the new sector's output is known from the total surplus agricultural land and projected productivity ($\Delta \bar{x}_{n+1}$). Assuming that the introduction of the new industry does not change the final demand of other industries ($\Delta Y = 0$), the I/O model becomes mixed endogenous/exogenous (see Miller and Blair [19] for a general description of this I/O model). Denoting exogenous variables with an overbar, Eq. (4) becomes:

$$\begin{bmatrix} (I - \tilde{A}) & -\tilde{C} \\ -A_{n+1,j} & (1 - \tilde{c}_{n+1}) \end{bmatrix} \times \begin{bmatrix} \Delta X \\ \Delta \bar{x}_{n+1} \end{bmatrix} = \begin{bmatrix} 0 \\ \Delta y_{n+1} \end{bmatrix} \quad (5)$$

The solution of this mixed I/O model is

$$\Delta X' = \begin{bmatrix} (I - \tilde{A})^{-1} C \\ \Delta \bar{x}_{n+1} \end{bmatrix} \quad (6)$$

$$\Delta Y' = \begin{bmatrix} 0 \\ \Delta \bar{x}_{n+1} - c_{n+1} - A_{n+1,j}(I - \tilde{A})^{-1} C \end{bmatrix} \quad (7)$$

where vector C presents the input costs from original industries that are necessary to produce output $\Delta \bar{x}_{n+1}$ of the new industry ($C = \tilde{C}\,\Delta \bar{x}_{n+1}$) and c_{n+1} is the input cost of the new industry necessary to produce its own product $\Delta \bar{x}_{n+1}$ (i.e.: $c_{n+1} = \tilde{c}_{n+1}\,\Delta \bar{x}_{n+1}$).

The solution shows that the change in total output of the original sectors is affected by the change in intermediate demand due to the introduction of the new product (represented by the modification of the technology matrix from A to $\tilde{A}$). The final demand of the new sector is equal to the total output minus the intermediate consumption of the new sector itself (c_{n+1}) and minus the intermediate consumption of the original sectors ($A_{n+1,j}(I - \tilde{A})^{-1} C$). The remainder is then the amount available for export (assuming no household consumption of the new sector's product). Having found the solution of the I/O model, the change in total output ($\Delta X'$) is used for determining the indirect macroeconomic impacts, as will be explained in Section 2.3.2.

2.3.1. Closed I/O model

The basic I/O model (also called an *open* I/O model) described above does not take into account the interactions of household income earned from the economic activity or the re-spending of this income on consumer goods, the so-called induced impacts [19,20]. The re-spending is considered exogenous in the open I/O model; household income from labour activity is part of the value added category and household spending is part of final demand. In order to actually account for these interactions, the household income and household spending can be "endogenised" by taking the household sector as another economically connected production sector.

To see the relationship between the open and closed model, the *open* I/O model (Eq. (5)) is rewritten to take the household's income-spending balance into account:

$$\begin{bmatrix} (I - A) & -H_c \\ H_r & -1 \end{bmatrix} \times \begin{bmatrix} X \\ x_h \end{bmatrix} = \begin{bmatrix} Y_{nh} \\ y_h \end{bmatrix} \quad (8)$$

where Y_{nh} is the final demand minus the household demand $Y_{nh} = [y_{ih}]$, i.e.: $Y_{nh} = Y - Y_h$; y_h is the household savings and equal to the difference between household income and spending: $y_h = (\sum_{i=1,\ldots,n} h_{ir} X_i) - x_h$; x_h is the total household demand for goods and services produced in all n sectors, i.e.: $x_h = \sum_{i=1,\ldots,n} y_{ih}$; vector $H_c = [h_{ic}]$ represents the household's spending structure where the household consumption coefficient is determined by $h_{ic} = y_{ih}/x_h$; and vector $H_r = [h_{ir}]$ represents the unit labour cost of sector i; the coefficients h_{ir} are determined by dividing household income from one sector by the total output of the sector, x_i.

In the open model, the household savings (y_h) are endogenous (as they can be calculated by subtracting the expenditure of the household sector from the income after the open model is solved) so that they do not affect the solution of the open model. The closed model assumes an exogenous savings level (y_h), and household spending, therefore, influences the solution of the closed model. It is assumed here that all household income generated by the new bioenergy sectors will be spent on domestic goods and services. In terms of the model variables, this means that household savings remain unchanged after the introduction of the new sector ($\Delta y_h = 0$). The exogenous variables are solved for as in the open model, and the resulting change in total output is then used in the calculation of the induced macroeconomic impacts, as is explained in the next section.

2.3.2. Direct, indirect and induced impacts

The direct impact of the bioenergy sector on GDP encompasses all value added (such as income from labour or capital, land rent and taxes minus subsidies) generated as a result of the new sector's output $\Delta \bar{x}_{n+1}$. Similarly, the direct impact of this sector on imports equals the amount of money spent on imported goods necessary for producing $\Delta \bar{x}_{n+1}$, and direct employment impacts are the number of jobs necessary for producing $\Delta \bar{x}_{n+1}$.

To determine the indirect impacts, Eq. (5) is solved, and the resulting change in total output of other sectors ($\Delta X'$) is calculated. To convert this change in total output to indirect impacts on GDP, imports and employment each element of the vector $\Delta X'$ is multiplied with the corresponding normalised GDP, import and employment coefficient specific to each sector, where the normalised GDP, import and employment coefficients represent the amount of value added, amount of import needed or employment needed per unit of output (in monetary terms). The direct impacts are subtracted as these would otherwise be double-counted.

To determine the induced impacts of bioenergy, the closed I/O model is solved with the additional assumption that all extra household income generated by new bioenergy sectors will be spent on domestic goods and services as described above. The induced impact is then equal to the change in total output of other sectors ($\Delta X'$) as generated from the closed I/O model multiplied by the normalised GDP, import and employment coefficients, respectively. As this determines the overall impact, the direct and indirect impacts determined above are subtracted.

2.4. Determining macroeconomic impacts of bioenergy production in Argentina

2.4.1. Input and output structures of new bioenergy sectors in Argentina

To determine the impacts of the pellet chain, two new sectors, eucalyptus production and pellet production, are added to the technology matrix in order to account for the impacts that these new activities have on the macroeconomic situation in Argentina. Distinguishing the two sectors is done because they have different input structures, and an aggregation of the two could cause a bias in results. For the FT fuel chain, three sectors are distinguished (eucalyptus production, pellet production and FT fuel production) in order to determine the macroeconomic impact of a more processed product.

For each new sector, an input cost structure is created by calculating the average production costs, assigning each cost item to the sector in which it is produced and then dividing by the total average costs to determine the technical coefficients of the bioenergy sectors. The assignment of a cost item to a specific sector is based on the sector classification used for the *I*/*O* tables of the Global Trade Analysis Project (GTAP)[5] from which the Argentinean *I*/*O* table is obtained [23].

Regarding the output distribution in Chain 1, it is assumed that the eucalyptus wood is solely used by the pellet production sector and that all pellets are assigned to export (the effect of consuming a portion of the pellet output domestically is checked in the sensitivity analysis, Section 4.4). For Chain 2 it is assumed that all eucalyptus wood is used in the pellet sector and all output from the pellet sector is consumed by the FT fuel sector. There are two outputs of the FT fuel sector: FT fuel, which is assumed to be exported entirely, and surplus electricity, which is assumed to be used by the largest electricity consumers in Argentina. Here 20% of the surplus electricity is assigned to be sold to the heavy manufacturing sector, 50% to the grid (utility sector) and 30% to the services sector.

2.4.2. Relative macroeconomic impacts of bioenergy production

In order to allow a comparison of the macroeconomic impacts determined by this study with results from literature, relative macroeconomic impacts of bioenergy production (excluding the impacts of agricultural intensification) are determined following the methodology described above and applying the bioenergy production costs per GJ as $\Delta\bar{x}_{n+1}$.[6]

2.4.3. Overall macroeconomic impacts of bioenergy production on surplus agricultural land in 2015

In order to determine the influence of agricultural intensification on the macroeconomic impacts of bioenergy production on surplus agricultural land, the impacts of bioenergy production only are compared to the impacts of bioenergy and agricultural intensification. The former is calculated like the relative impacts except that now the total output of the bioenergy sector $\Delta\bar{x}_{n+1}$ equals the surplus agricultural land area multiplied with the bioenergy production costs per hectare (assuming that this amount of land could also be made available by activities other than agricultural intensification). This is simply an extrapolation of the relative impacts of bioenergy production for the total surplus land area and does not account for the direct impacts of agricultural intensification and the changes in the resulting input structures of the agricultural sectors and in the macroeconomic impacts of bioenergy production.

In order to account for these impacts, the direct impacts of agricultural intensification and of bioenergy production and the indirect and induced impacts of bioenergy production on surplus agricultural land are determined as follows. The direct impact of agricultural intensification on GDP (imports/employment) is determined by multiplying the current total output of Argentina's two agricultural sectors (assuming that the sector output is not affected by the intensification) first with the GDP (import/employment) coefficients of the advanced agricultural production, then with the GDP (import/employment) coefficients associated with the reference situation and then by taking the difference between these two calculations. Assuming a constant output of the two agricultural sectors is a simplification that allows singling out the effects of agricultural intensification from effects caused by changes in the output of the agricultural sectors.

To calculate the indirect and induced macroeconomic impacts of bioenergy production on surplus agricultural land for Argentina, the same approach is used as for calculating the impacts of bioenergy production only (applying the total output of the bioenergy sector, determined by multiplying the surplus agricultural land area with the bioenergy production costs per hectare, as $\Delta\bar{x}_{n+1}$) but now applying a new technology matrix, which differs from the old matrix only by the *I*/*O* coefficients associated with agricultural sectors (distinguished for agricultural crop sector and livestock sector). The coefficients of the new, intensified agricultural sectors are based on the coefficients of another country that is more technologically advanced than Argentina and whose current agricultural production characteristics are comparable to those projected by the Quickscan model for Argentina in 2015. To find such a country, parameters of comparison are taken to be the yields of major crops for the agricultural crop sector and the feed composition and feed conversion efficiency for the livestock sector. After identifying the most representative country, the country's input coefficients for the agricultural sectors are used as proxies for Argentina's advanced agricultural production technology in 2015.

3. Input data

3.1. Technology matrix

The *I*/*O* table for Argentina is retrieved from the GTAP data base 6 and refers to year 2001 [24].[7] The original Argentinean *I*/*O* table with 57 sectors is aggregated to 14 sectors based on the sector description used in GTAP [23] (for an overview of sector aggregation see Table A in the Electronic Annex in the online version of this article). The representativeness of and the uncertainty caused by using the 2001 *I*/*O* table for projections for 2015 are discussed in Section 5.2.

3.2. Coefficients of bioenergy sectors

The total biomass production costs include plantation costs such as land rent, site preparation, planting, maintenance and harvest as well as biomass transportation costs from within the plantation to the roadside and from the roadside to the pellet plant [14,25–27]. Storage at roadside, low land costs and abundance of land at roadsides make the storage cost at roadside negligible [16].

An average yield of 35 m^3 ha^{-1} $year^{-1}$ (15 t dry matter ha^{-1} $year^{-1}$) is assumed, but yields in literature range from 20 m^3 ha^{-1} $year^{-1}$ (8 t dry matter ha^{-1} $year^{-1}$) in the northwest [16] to

[5] The Global Trade Analysis Project is a worldwide network of researchers and policy makers who conduct quantitative analyses of international policy issues, particularly with respect to global economic issues (for more information see the project website: https://www.gtap.agecon.purdue.edu/).

[6] Unless noted otherwise, all reference to energy refers to primary energy and energy content is expressed as lower heating value.

[7] Unless noted otherwise, all monetary values in this article are given in 2001 US dollar.

Table 2
Production parameters of *Eucalyptus grandis* and pellets in Argentina.

Parameter (unit)	Value	Source
Eucalyptus wood production		
Density of wood (t dm m^{-3})	0.42	[26]
Density of plantation (plants ha^{-1})	1111	[25,27]
HHV (GJ t^{-1} dm)	19.7	[14]
Moisture content at harvest (%)	55	[26]
Moisture content dried in field for 3 months (%)	26	[26]
Pellet production		
Energy content of pellets, average (LHV) (GJ t^{-1})	17.5	[39]
Pellet moisture content (%)	10	[39]
Electricity cost 2005 (US$ MW h^{-1})	27.5	[40]

60 m^3 ha^{-1} $year^{-1}$ (25 t dry matter ha^{-1} $year^{-1}$) on experimental fields in the northeast of Argentina [16]. Other production data obtained from interviews and data collection in Argentina is presented in Table 2. Since administration costs specific to eucalyptus production could not be retrieved, the percentage of these in the production costs of the forestry sector are used (10%) [16].

The pellet production system is assumed to be the same as the Swedish one studied by Thek and Obernberger [28], and since no pellet production cost data could be found for Argentina, the input data of the Swedish pellet production is used. However, when possible, Argentina-specific data is used (Table 2); for the remaining data see Thek and Obernberger [28].

For FT fuel production, use of an 800 MW input FT fuel plant that has annual sales volumes of approximately 250 million litres of diesel, 50 million litres of gasoline and 500 GWh of electricity is assumed. The investment costs of a FT fuel production plant are based on the work of van Vliet et al. [17] and are presented in more detail in Electronic Annex (Table B) in the online version of this article. An economic lifetime of 15 years and an interest rate of 10% are applied [29]. Additional cost items include maintenance (3% of total capital investment), labour costs (0.5% of total capital investment), gas cleaning (0.5% of total capital investment) and insurance (0.1% of total capital investment) [29].

Transport of biomass costs 0.09 US$ km^{-1} t^{-1} for short distances and 0.06 US$ km^{-1} t^{-1} for long distance with full load [16]. The costs of the empty return trip are assumed to amount to two-third of the full load transport costs.

3.3. Coefficients of agricultural intensification

Current crop yields in the United States [30] are comparable to the presumed yields of Argentina in 2015 while the US crop production system is also comparable to Argentina with respect to the fully mechanised, large-scale production of crops and the relatively few farmers owning and working large amounts of land [31]. The feed composition and feed conversion efficiency projected for the livestock sector of Argentina in 2015 are also comparable to those of the current US livestock production system now [2]. While there are likely to be differences in agricultural production in Argentina in 2015 and the US now, the lack of better data causes the use of the input coefficients of the current US agricultural production sectors as proxies for the advanced agricultural crop and livestock production sectors in Argentina in 2015. The input coefficients are retrieved from the US *I*/*O* table in the GTAP data base [32].

3.4. Normalised GDP, import and employment coefficients

The normalised value added and direct import coefficients are obtained from the Argentinean *I*/*O* table from GTAP [33]. Because the GTAP version does not include employment figures, the normalised employment coefficients for Argentina are derived from the 1997 *I*/*O* table for Argentina that also served as a basis for the 2001 Argentina *I*/*O* table from GTAP, assuming that employment coefficients from 1997 are comparable to 2001 [33]. Normalised value added and import coefficients for advanced agricultural production are obtained from the US *I*/*O* table [32]. The normalised employment coefficients of advanced agricultural production are based on employment data from the Bureau of Labor Statistics of the US Department of Labor [34] and on the total agricultural sector output data from the US *I*/*O* table [32].

4. Results

4.1. Bioenergy production costs

Before presenting the macroeconomic impacts of bioenergy production, the production costs of bioenergy are shown. These production costs are intermediate results and are further used to determine the technical coefficients of the bioenergy sectors for the extension of the *I*/*O* model and as $\Delta\bar{x}_{n+1}$ for the calculation of the macroeconomic impacts.

Eucalyptus wood production costs are determined to be 0.98 US$ GJ^{-1} (18 US$ t^{-1} dry matter), which is comparable to estimates for Argentina by the Argentinean Ministry of Agriculture (SAGPyA) [16] and other studies on woody bioenergy crop production, for example by Batidzirai et al. [35] for Mozambique. The pellet production costs determined by this study amount to 4.1 US$ GJ^{-1} (72 US$ $t_{pellets}{}^{-1}$), which is comparable to production costs in Latvia in 1998 [36], but slightly higher than in Sweden and lower than in Austria [28]. The FT fuel production cost found in this study is 17 US$ GJ^{-1} (0.8 US$ $l_{FT\ fuel}{}^{-1}$). This result is similar to the production cost of 15.7 US$ GJ^{-1} (16 €$_{2002}$ $GJ_{HHV}{}^{-1}$) found by Hamelinck et al. [29] who studied a smaller scale plant (400 MW_{th} input) with a circulated fluidized bed gasifier.

4.2. Relative impacts of bioenergy production

Table 3 presents the relative macroeconomic impacts of pellet production (Chain 1) and FT fuel production (Chain 2). Large variations in impacts among various studies in the literature and in comparison to these results are found. Previous literature on the macroeconomic impacts of bioenergy production shows direct and indirect impacts on GDP to range from 0.15 to 2.3 US$ GJ^{-1} [3,9] and on employment to range from 80 to 800 jobs PJ^{-1} [6,37]. While the impacts on GDP found in this study are significantly higher than those found in literature, employment according to this study lies within the range found in literature and is comparable to the lower end of the range (Table 3). Direct and indirect impacts on imports can only be found in the work of van den Broek et al. [3], who estimates these to be 1.1 US GJ^{-1}. This is significantly larger than the results for Chain 1 but comparable to Chain 2. The differences in results of this study and literature findings may be

Table 3
Relative impacts of bioenergy production on GDP, imports and employment.

Chain	GDP		Import		Employment	
	US$ GJ^{-1}		US$ GJ^{-1}		Jobs PJ^{-1}	
	1	2	1	2	1	2
Direct	1.2	2.9	0.3	0.8	96	101
Indirect	2.3	2.8	0.2	0.3	157	199
Induced	2.0	2.4	0.2	0.2	158	192
Total	5.4	8.0	0.7	1.3	411	492

Note: Due to rounding, the total may not correspond to the sum of the individual figures.

explained primarily by (1) including or excluding biomass processing in the analysis and (2) the different management systems applied in the specific cases (for example manual versus mechanical work). Because details on the type of management system applied and the activities included are seldom given, a comparison of results from literature and from this study is difficult. A part of the large variation in macroeconomic impacts may also be attributed to the distinct economic structure of each country making direct comparison of *I*/*O* analysis results from different countries difficult. Induced impacts are not included in the comparison because they have not been studied previously for bioenergy. However, that indirect and induced impacts are generally very similar in size for all variables in both chains (Table 3) indicates that the induced impacts are quite significant and that the re-spending of income from the bioenergy production sector can contribute considerably to economic growth and employment generation.

The FT fuel chain generated more positive macroeconomic impacts than the pellet chain (GDP and employment), implying that further processing of bioenergy results in greater impacts in Argentina. Although there are larger requirements for imports such as machinery and equipment parts not produced in Argentina, the export of a higher quality and higher priced bioenergy product negates this problem. While additional jobs are created by the processing of pellets to FT fuel, the effect is much smaller than for value added and imports (Table 3).

The breakdown of impacts by sector shows that the composition by impact type (direct, indirect and induced) differs for each sector (presented graphically for GDP in Fig. 1. Large effects on all three variables are found in the new bioenergy sectors as well as in the heavy manufacturing sector, which is due to the fact that a large amount of machinery and equipment is bought from this sector. There is also a significant impact on the transport sector, especially for GDP and employment, which may be explained by the high transportation costs in Argentina (giving transport a large share in the input structure of the bioenergy sectors). This exposes a general problem of *I*/*O* analysis: the more expensive an input product is, the larger the associated sector's input coefficient and the larger the indirect effects will be in this sector. However, transportation's high relative cost does not necessarily mean that new bioenergy production will create more jobs in the transport sector, despite the *I*/*O* analysis' conclusion to this effect.

4.3. Overall impacts of bioenergy production on surplus agricultural land

Based on an intermediate level of agricultural advancement, the Quickscan model results in 28 Mha suitable, surplus land for Argentina. Comparing the resulting permanent pasture and arable land with the reference situation in 2001 [30] shows that most of the surplus land was originally permanent pasture land and is freed by an intensification of livestock production. On the one hand, this may be explained by that agricultural crop production in Argentina is already now quite advanced and that therefore only little land can be freed. On the other hand, livestock production in Argentina, which is currently almost entirely grass-fed, is projected by the Quickscan model to become an entirely mixed feeding system in 2015 (see Table 1). As a result of this substantial change in feeding composition, large areas of land may be freed from livestock production.

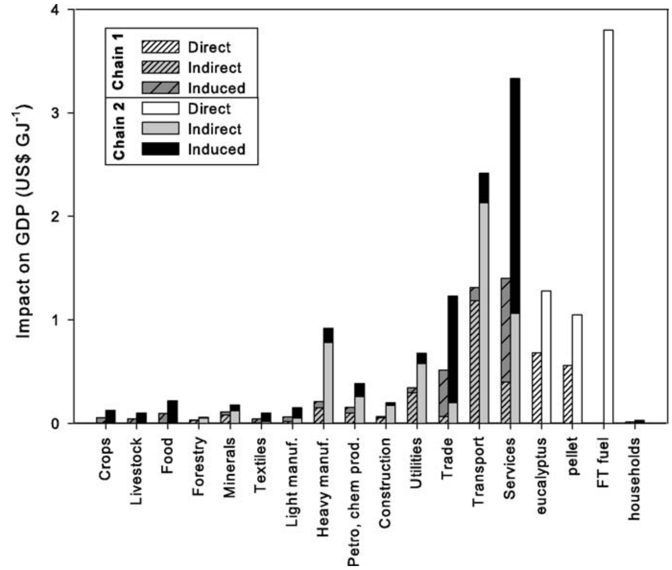

Fig. 1. Breakdown of relative impacts on GDP by economic sectors and impact type.

The surplus agricultural land area of 28 Mha represents 10% of the total Argentinean land area and, in this projection, would produce 537 Mt (26% moisture content) of wood, which is equivalent to 442 Mt of pellets or 85 billion litres of FT fuel. Producing this amount of bioenergy results in large macroeconomic impacts compared to the reference situation in 2001 (Table 4). Compared to 2001, Chain 1 causes an increase of 18% in GDP, 20% in imports and 26% in employment, while Chain 2 causes increases of 25%, 35% and 29% for these variables, respectively. It should be noted that these extrapolations do not account for scaling or learning effects in bioenergy production, which, on such a large scale, are expected to reduce the cost of production, and therefore, in *I*/*O* terms, the demand for products.

Table 4
Extrapolation of macroeconomic impacts of bioenergy production on agricultural surplus land in Argentina.

	GDP		Import		Employment	
	Million US dollars		Million US dollars		1000 jobs	
	Chain 1	Chain 2	Chain 1	Chain 2	Chain 1	Chain 2
Bioenergy	43 863	64 959	5754	10780	3337	3998
Direct	9 608	23 226	2840	6294	781	820
Indirect	18 302	22 436	1249	2459	1272	1615
Induced	15 953	19 297	1664	2028	1285	1564
Change from 2001 (%)	18	25	20	38	26	29
Agricultural intensification	−3837	−3625	110	138	−1253	−1246
Direct	−3761	−3761	94	94	1027	1027
Indirect and induced	−76	−136	17	44	−46	39
Bioenergy and agricultural intensification – overall impacts	40 027	61 334	5864	10 917	2084	2752
Change from 2001 (%)	16	25	20	38	16	21
Relative impact of agricultural intensification (%)	−9	−6	2	1	−38	−31

Table 5
Parameter variation for sensitivity analysis (Chain 1).

Parameter (unit)	Base case	Low	High	Source/remarks
Eucalyptus price (US$ GJ^{-1})	1.0	0.5	1.6	Low: [35]; high: [3]
Pellet price (US$ t^{-1})	72	58	84	Low: [28]; high: [28]
Import coefficient of pellet sector (dimensionless)	0.08	0	0.12	Lower bound represents no import, upper bound is equal to importing all machinery and equipment
Coefficients of agricultural intensification				
GDP (US$ GJ^{-1})				Agri. crops: upper bound equals original coefficient, others are varied with same percentage
Agricultural crops	0.58	0.52	0.64	
Livestock	0.23	0.21	0.25	
Trade balance (US$ GJ^{-1})				Agri. crops: lower bound equals original coefficient, others varied with same percentage
Agricultural crops	0.03	0.02	0.05	
Livestock	0.04	0.02	0.06	
Employment (Jobs PJ^{-1})				
Agricultural crops	10	50%	200%	
Livestock	13	50%	200%	
Coefficients for bioenergy sectors				
GDP (US$ GJ^{-1})				Pellet: upper limit represents no imports, others are varied with same percentage
Eucalyptus	0.71	0.57	0.86	
Pellet	0.14	0.11	0.16	
Trade balance (US$ GJ^{-1})				
Eucalyptus	0.03	50%	200%	
Pellet	0.08	50%	200%	
Employment (Jobs PJ^{-1})				
Eucalyptus	84.5	50%	200%	
Pellet	2.6	50%	200%	
Export share/output structure[a] (%)	100	80%	–	Lower bound assumes that 20% of the produced bioenergy is consumed in Argentina
Surplus agricultural land (Mha)	28	50%	150%	

[a] In the case that bioenergy is also consumed in Argentina, 15% of this is assumed to be used by the utility sector replacing inputs from mineral sector; 50% is assumed to be used by the heavy manufacturing sector replacing inputs from services, utilities and heavy manufacturing; and 35% is assumed to be used by services replacing inputs from the service sector itself.

Agricultural intensification has negative macroeconomic impacts, reducing the positive impacts of bioenergy on GDP and employment, but not negating them (Table 4). Agricultural intensification causes a 9% and 6% decrease in the GDP impacts of bioenergy production in Chain 1 and 2, respectively. Employment is affected most by agricultural intensification, which causes the impacts to reduce by 38% for Chain 1 and 33% for Chain 2. While on a macro-level the reduction in employment in the agricultural sector can be compensated by the additional employment generated by bioenergy production, individuals loosing their jobs in agriculture may not be the same ones hired by the bioenergy industry. Agricultural intensification also causes a further increase in imports because more machinery, fertilizer or other agricultural inputs must be imported, but this increase is small (2% and 1% for Chain 1 and 2, respectively). The size of the change depends largely on the agricultural sectors' import coefficient, which, in this case, is taken from the US *I*/*O* table to represent the advanced agricultural production system in Argentina in 2015. However, the US produces more machinery and equipment domestically and requires fewer imports than Argentina, meaning that the increase in imports in Argentina may be underestimated. The effect of this uncertainty is studied in the sensitivity analysis below. While the imports for bioenergy production and agricultural intensification significantly increase the current national import spending, the increase in bioenergy exports is even larger so that the bioenergy sectors still have a significant trade surplus.

Despite the considerable negative impacts of agricultural intensification, the overall impacts of large-scale bioenergy production on agricultural surplus land in Argentina are positive and large, causing GDP to increase by 16% and 24%, imports by 20% and 35% and employment by 16 and 19% for Chain 1 and Chain 2, respectively (Table 4).

4.4. Sensitivity analysis

In the sensitivity analysis seven parameters are checked for their uncertainty and for their effect on the results of the macroeconomic impacts of Chain 1 (Table 5). Because similar effects are found for Chain 2, only the sensitivity analysis for Chain 1 is presented here (Fig. 2). The sensitivity analysis indicates that the overall macroeconomic impacts of bioenergy production on surplus agricultural land are most sensitive to the amount of land that can be freed from agriculture. A discussion of the uncertainties in the extent of surplus agricultural land is given in Section 5.3.

Two other factors cause large variations in the outcomes. These are the eucalyptus price and pellet price (Fig. 2). In *I*/*O* analysis, an increase in the price of wood (or pellets) will cause more money to be spent—even if the demand for wood from the pellet sector remains the same. This, in turn, is translated by the *I*/*O* model into larger macroeconomic impacts, a general problem of *I*/*O* analysis [12].

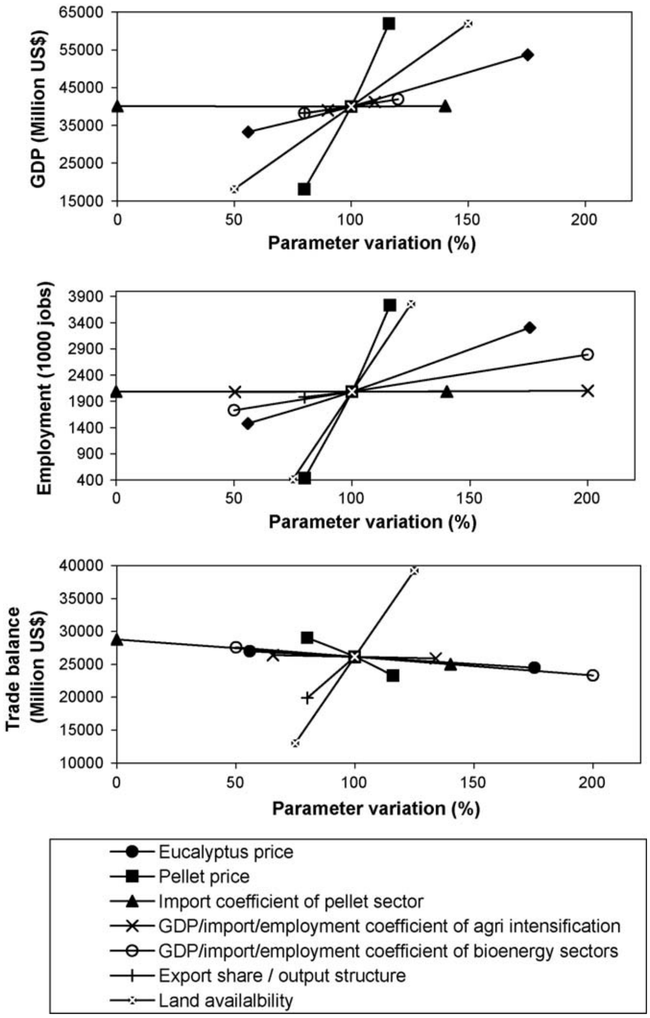

Fig. 2. Sensitivity analysis of impacts on GDP (top), employment (middle) and trade balance (bottom) from Chain 1.

The trade balance results are very sensitive to variations in the export share of the bioenergy produced. But this variation also negatively affects GDP and employment, although the effect is much smaller than for the trade balance. This effect on also GDP and employment may be explained by the changes in sectoral interlinkages that result from higher domestic consumption: it is assumed that, if a bioenergy sector supplies to one of the original sectors, for example, the utility sector, another sector will provide less inputs to the utility sector so that the utility sector's output remains constant.

The variation of factors that are highly uncertain, i.e. GDP, imports and employment coefficient of agricultural intensification, shows little impact on the results. The results are also not sensitive to a variation in the GDP, imports and employment coefficients of the bioenergy sectors (Fig. 2).

5. Discussion

5.1. Argentina as a case study

Although Argentina is considered a developing country, it is in many ways an anomaly among the developing world because it exhibits a number of highly developed economic sectors. For example, Argentina's highly developed agriculture contrasts with the labour-intensive, low-machinery subsistence farming employed in many other developing countries. The result of this difference is that other, less developed countries are likely to experience much larger negative intensification impacts than Argentina. However, some of the negative effects of agricultural intensification in other countries may be reduced by the larger investments that are needed to reach the same level of agricultural advancement as projected for Argentina. But since a suitable methodology for determining the investments needed for making agricultural intensification possible is lacking, it will be difficult to assess whether these additional investments could compensate for the larger negative impacts of agricultural intensification. In addition to the differences in current agricultural production systems, the economic structure and sectoral interlinkages in Argentina may also differ significantly from other developing countries, thus making it more difficult to draw conclusions about the indirect and induced macroeconomic impacts of bioenergy production in those countries.

5.2. Input–output analysis

Despite its usefulness, *I*/*O* analysis has various shortcomings—some of which have already been mentioned throughout this paper. A general shortcoming not yet discussed is that *I*/*O* models inherently overstate impacts because they do not account for the possibility of substitution of inputs or for price effects [12]. The scale of this overestimation depends mainly on the degree to which these impacts influence relative prices. Non-linear simulation models, e.g. Computable General Equilibrium (CGE) models, may reduce this shortcoming because they more realistically represent relationships in the economy and thus more accurately project the impact of a new activity on the whole economy [12]. However, due to large data requirements for determining the model parameters and their relationships and due to their own problems such as price formation and market clearing processes, a CGE model was not utilised in this study.

An additional aspect of uncertainty of the *I*/*O* analysis in this study is the assumption that, while other sectors of the economy are kept unchanged, the agricultural sectors undergo a large transformation. Despite the improbability of such a skewed development, this assumption was made in order to be able to single out the effects of agricultural intensification from the effects of other sectoral changes on the macroeconomic impact of bioenergy production. In addition, it can be argued that projecting changes in the economy and the sectoral interlinkages would be highly uncertain considering only, for example, the erratic changes that occurred as a result of the economic crisis in Argentina in 2001–2003 and that are likely to occur as a result of the current global economic crisis. And, as a result, such projections may not increase the reliability of the resulting *I*/*O* table for 2015. Furthermore, two particular changes in the economy could be caused by increasing bioenergy production itself: firstly, Argentinean industry may invest more into domestic production of machinery and equipment required in pellet and FT fuel production, which would cause import shares as well as the input structures of, for example, the machinery sector to change. Doing so would internalise positive impacts that are now projected to leak abroad. Secondly, with increasing bioenergy production, eucalyptus production in particular may become more mechanised and thus have (possibly very) different impacts, especially with respect to employment. A manual-labour based eucalyptus production system was chosen because this is typical in current wood production in Argentina [16] and because Argentina-specific data is available for this production system.

5.3. Surplus agricultural land

The method for determining the extent of surplus agricultural land generated by agricultural intensification in Argentina is based

on Smeets et al.'s Quickscan model, which was originally set up to calculate the theoretical regional and global biomass potentials in 2050 [2]. The main problem with applying the Quickscan model in this case study is that the South American average input data does not always reflect the Argentinean situation. Yet because the agricultural data required for the analysis, e.g. the feed conversion of the various animal categories for mixed and pastoral production systems and their fractions of the total production, is not available for Argentina specifically, the South American averages were used. One example of the differences between South American averages and Argentinean values is the data for the composition of mixed-fed versus pastoral non-dairy cattle production. South American averages used in the Quickscan model are 56% mixed-fed versus 44% pastoral. However, almost 90% of all beef production in Argentina is estimated to be grass-fed [38]. Since mixed-fed feed production is much more efficient than pastoral systems, the change to 100% mixed-fed livestock production could free more land in Argentina than it would in most of South America, which leads to an underestimation of the surplus agricultural land area. While this example shows how South American averages may differ from Argentina, the data from this example is not applied to the analysis because of the inadequately defined USDA standards of grass-fed beef production systems regarding the percentage of non-grass feed in total feed input [38]. No other country-specific data for better projecting agricultural intensification in Argentina could be retrieved. This lack of data allows neither determining how strongly other parameters of agricultural production differ from the South American averages nor establishing the level of uncertainty in the amount of surplus agricultural land.

It is important to stress that the amount of surplus land determined in this study may only become available in the future if agriculture intensifies substantially. This requires the introduction of more efficient technology, the financing systems required for such technology and changes in the agricultural and silvicultural management systems, all of which depend largely on the choices made by Argentinean policy makers. In addition to the uncertainties about the amount of land freed by agricultural intensification, also the amount actually available for bioenergy production is disputable as bioenergy will compete with other land use forms, such as biodiversity conservation or rehabilitation.

6. Conclusion

This paper's objective of determining the macroeconomic impacts of bioenergy production on surplus agricultural land is tackled by developing an *I/O* model and applying it to Argentina. Producing bioenergy on the projected 28 Mha surplus land would result in large positive macroeconomic impacts. Compared to the reference situation of 2001, total national GDP increases by 16% for the pellet chain (*Chain 1*) and 25% for the FT fuel chain (*Chain 2*). Similar increases could be found for employment, which increased by 16% and 21% for Chains 1 and 2, respectively, compared to the reference situation. The effects on imports are significantly larger for *Chain 2*, for which an increase of 38% is recorded, compared to 20% in *Chain 1*. *Chain 2*'s larger increase in imports is balanced out by a large increase in exports.

This study has demonstrated that agricultural intensification impacts are negative but do not negate the positive impacts associated with bioenergy production in Argentina. However, the negative impacts of agricultural intensification are significant, and they should not be ignored in the macroeconomic assessment of large-scale bioenergy production. Also, Argentina may not be representative of other developing countries because Argentina has an unusually well-developed agricultural production system that is more comparable to industrialised countries such as the United States than to other developing countries. It is therefore recommended that future macroeconomic impact assessments of bioenergy production examine the intensification impacts in a more "typical" developing country.

This study exposed several limitations of the *I/O* analysis and of the method for projecting agricultural intensification. Despite these limitations, the methodology developed here serves as a reliable tool for approximating the macroeconomic impacts of large-scale bioenergy production in combination with the effects of agricultural intensification. In addition to the macroeconomic impacts of agricultural intensification, other sustainability aspects such as the environmental implications of such intensification require further attention in future research on bioenergy production on surplus agricultural land.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.rser.2009.05.010.

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